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Potential for Production of Perennial Biofuel Feedstocks in Conservation Buffers on the Coastal Plain of Georgia, USA

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Abstract With global increases in the production of cellulosic biomass for fuel, or "biofuel," concerns over potential negative effects of using land for biofuel production have promoted attention to concepts of agricultural landscape design that sustainably balance tradeoffs between food, fuel, fiber, and conservation. The Energy Independence Security Act (EISA) of 2007 mandates an increase in advanced biofuels to 21 billion gallons in 2022. The southeastern region of the USA has been identified as a contributor to meeting half of this goal. We used a GIS-based approach to estimate the production and N-removal potential of three perennial biofeedstocks planted as conservation buffers (field borders associated with riparian buffers, and grassed waterways) on the Coastal Plain of Georgia, USA. Land cover, hydrology, elevation, and soils data were used to identify locations within agricultural landscapes that are most susceptible to runoff, erosion, and nutrient loss. We estimated potential annual biomass production from these areas to be: 2.5–3.5 Tg for giant miscanthus (*Miscanthus*×*giganteus*), 2–8.6 Tg for "Merkeron" napier grass (*Pennisetum purpureum*), and 1.9–7.5 Tg for "Alamo" switchgrass (*Panicum virgatum*). When production strategies were taken into consideration, we estimated total biomass yield of perennial grasses for the Georgia Coastal Plain at 2.2–9.4 Tg year^{-1}. Using published rates of N removal and ethanol conversion, we calculated the amount of potential N removal by these systems as 8100–51,000 Mg year^{-1} and ethanol fuel production as 778–3296 Ml year^{-1} (206 to 871 million gal. US).

Keywords Biofuel · Bioenergy feedstocks · Landscape analysis · *Miscanthus*×*giganteus* · *Pennisetum purpureum* · *Panicum virgatum* · Georgia Coastal Plain

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Abbreviations

AOI	Area of interest
CW	Conservation waterway
EISA	Energy independence and security act of 2007
CRP	Conservation reserve program
GHG	Greenhouse gas
GIS	Geographic information system
gSSURGO	Gridded soil survey geographic data
K	Potassium
N	Nitrogen
NAIP	National agriculture imagery program
NCDL	National cropland data layer
NED	National elevation dataset
NLCD	National land cover database
NRCS	Natural resources conservation service
mamsl	Meters above mean sea level
MLRA	Major land resource area
P	Phosphorous
RB	Riparian buffer
US-EPA	US Environmental Protection Agency

USA	United States of America
USDA	United States Department of Agriculture
USGS	United States Geologic Survey

Introduction

With global increases in the production of cellulosic biomass for fuel, or "biofuel", concerns over potential negative effects of using land for biofuel production have promoted attention to concepts of agricultural landscape design that sustainably balance tradeoffs between food, fuel, fiber, and conservation [1]. Concerns over the use of cultivated land for biofuels revolve around some key points, among them: the removal of crop land from food production in light of the increasing "calorie gap" between what is produced on crop lands and what is needed to sustain human populations into the future [2], and the net landscape ecological and energy effects of converting untilled or conservation acreage to crops (e.g., *Zea mays* L.), including negative impacts to biodiversity, soil conservation, water quality, and GHG emissions [3].

In the USA, production for corn-based ethanol has been increasing in response to policy directives aimed at stimulating the development of biofuels, with 84 million dry tons in production in 2014. Although this amount is estimated to increase to 88 million dry tons by 2017, the amount of bioethanol from corn and corn starch should remain fairly constant into 2020 [4, 5]. "Second-generation" cellulosic biofeedstocks are among the several types of "advanced biofuels" that, as defined by the Energy Independence Security Act (EISA) of 2007, include sources of fuel "other than ethanol derived from corn starch, that [have] lifecycle greenhouse gas emissions, …, that are at least 50 percent less than baseline greenhouse gas emissions" [6]. Thus far, second-generation biofeedstocks have not played a significant role; the proportion of their contribution is projected to increase substantially in the coming decade in accordance with the EISA [6, 7], which mandates an increase from 3 to 16 billion gallons in 2015–2022. Toward the overall goal for advanced biofuels—21 billion gallons by 2022—the US Department of Agriculture (USDA) reported that the Southeastern region could contribute 49.8 % from sources such as perennial grasses and biomass sorghum, among others [8].

The southeastern region of the USA, known as the Southern Coastal Plain and, alternately, the Southeastern Plains (Fig. 1), has been noted as highly suitable for biofeedstock production [9, 10] where warm-season perennial grasses including giant miscanthus (*Miscanthus × giganteus* J.M.Greef & Deuter ex Hodk. & Renvoize), switchgrass (*Panicum virgatum* L.), and napier grass (*Pennisetum purpureum* Schumach.) have shown high yields in production models and experimental plots [11–13]. Switchgrass and giant miscanthus, in particular, have been recommended as dedicated bioenergy feedstock crops in the region due to high yield and relatively low input needs [14–16]. Giant miscanthus yields in the region have been reported as being somewhat lower than yields in the more northerly central Midwest, averaging 9–10 Mg DM ha^{-1} over several years [12, 17]. Yield of Alamo switchgrass in the Coastal Plain of Georgia reached 17 Mg DM ha^{-1} over multiple years and locations compared with 28 Mg DM ha^{-1} for Merkeron napier grass [10]. However, miscanthus and switchgrass convert to reproductive growth in July for much of the southern Coastal Plain which may limit biomass production. In comparison, napier grass will produce much higher dry matter yields in the Southeast due to flowering much later in the growing season [18]. Napier grass has reached 60 Mg DM ha^{-1} at some locations, but generally, 30 Mg DM ha^{-1} would be the maximum expected with adequate soil nutrients in the northern regions of adaptability [19, 20]. Napier grass can be invasive if grown in frost-free areas of the southern part of Florida where seed heads may develop and mature during the late fall. There, naturalized clones of napier grass are an invasive weed for sugar cane in particular, and, due to this characteristic, *Pennisetum purpureum* was not included in a recent "white list" of bioenergy feedstocks [21]. However, biofeedstock clones of napier grass differ morphologically and physiologically from naturalized clones, indicating that the risk of invasiveness is not species-wide and that risk assessments of invasiveness in napier grass should occur at the clone level [13, 22]. Therefore, we included Merkeron napier grass in the portfolio of options for biofuel production in Georgia's Coastal Plain, where, we observed, it behaves as a sterile cultivar.

In addition to biomass yield considerations, perennial grasses offer conservation benefits by stabilizing soils and removing excess nutrients from agricultural runoff before they might reach aquatic systems and diversifying agricultural landscapes [23]. Miscanthus and switchgrass require less water and nutrients than many other feedstocks [24] and are moderately tolerant of flooding and heat [25]. Knoll et al. found that unfertilized napier grass tended to remove nearly twice as much N than switchgrass at harvest [18]. Knoll et al. also observed that napier grass produced under fertilization (NPK = 100, 40, and 90 kg ha^{-1} year^{-1}, respectively) removed an average of 225, 26, and 535 kg ha^{-1} year^{-1} (NPK respectively) during the peak year of production (30 Mg DM ha^{-1}) [26].

While the full measure of ecosystem services associated with second-generation biofeedstocks is still under scrutiny [27], the scenario of using of marginal lands to produce biofuels is one that addresses some of the land use concerns mentioned above [28] and has been incorporated into recent biofuel production models and discussions [9, 29–31]. In this context, marginal lands are areas where cultivation is possible

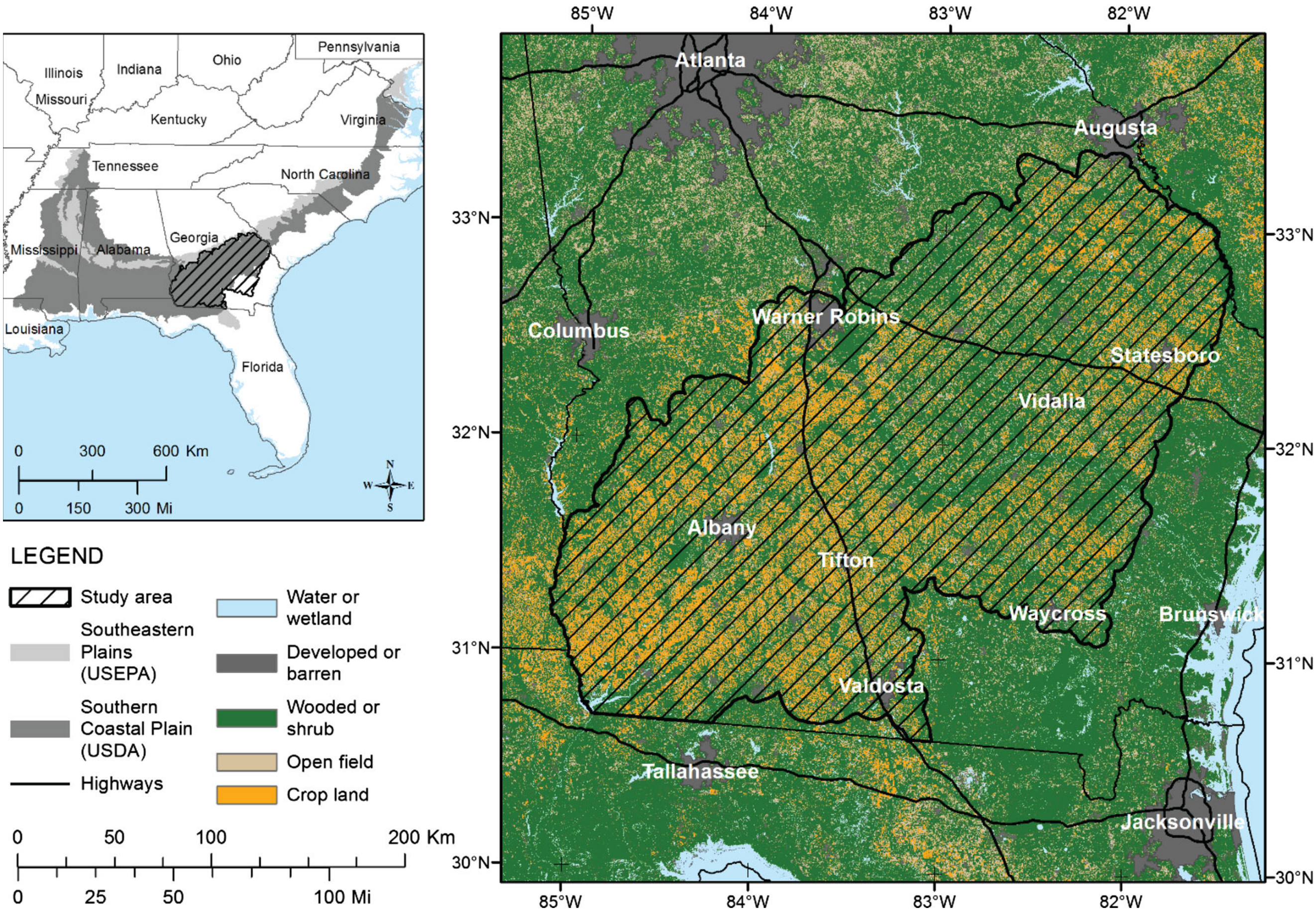

Fig. 1 Map showing the study area in the southeastern coastal plains of Georgia. Base modified from: U.S. Geological Survey NLCD 2011 Land Cover 30-meter resolution; U.S. Environmental Protection Agency Level III Ecoregions of the Conterminous United States, 2013; U.S. Census Bureau TIGER/Line Shapefile U.S. Primary Roads National Shapefile, 2014; U.S. 2010 Census Urban Area National, 2014

and may have once occurred, but where conservation benefits strongly favor the removal of these lands from active crop production. Such marginal lands are a primary focus of the Conservation Reserve Program (CRP) sponsored by the USDA Natural Resources Conservation Service (USDA-NRCS; www.nrcs.usda.gov), which enlists private land owner cooperation by offering payment in exchange for conservation and whose annual enrollment averages 13.3 M ha^{-1} since 1990 [32].

Riparian buffers and grassed waterways are key marginal land management tools utilized by the NRCS that conserve soils and enhance water quality of agricultural landscapes, as plants in the buffers intercept and utilize nutrients in the runoff, and reduce soil erosion. Grassed waterways are constructed channels that are "established with suitable vegetation" and are typically located within crop fields where runoff concentrates, and where erosion would otherwise occur [33]. A spatial concept of riparian buffers is depicted in Fig. 1 of Hubbard and Lowrance (1994, p. 385) [34], whereby management intensifies with distance upslope from the stream or river edge using an arrangement of zones. Beginning at the stream edge, the first zone, minimally 5 m wide, is permanent unmanaged forest adjacent to the stream corridor. Moving out from the first zone, the second zone is a variable width (~50 m) forest managed for "maximum biomass production." Yet, farther from the stream edge, zone three is a ~10-m wide strip of mowed grass between zone two and the crop field. The high rates of nutrient removal in harvested biomass suggest that napier grass may be an excellent choice as the grass member of this USDA-NRCS approved riparian buffer conservation practice. Because the dense bunchgrass characteristic of napier grass makes it a less desirable option for the grassed waterways where producers must have turn-around and pivot wheel access, giant miscanthus and switchgrass may offer better alternatives in these landscape positions.

This study builds on an overview by Lowrance et al. of potential biofeedstock production for the Coastal Plain of Georgia, USA. They estimated that strategically located 10-m waterways and riparian buffers could produce 215 M liters of ethanol per year [9]. Here, we used a Geographic Information Systems (GIS)-based approach to estimate the biomass production and N-removal potential of three perennial biofeedstocks for two categories of landscape features found throughout the region and typically associated with conservation easements targeted to the protection of highly erodible land and water quality: field borders associated with riparian buffers and grassed waterways within crop lands. For the former, we explored the deployment of a 20-m wide strip in the outer zones of the riparian buffer, avoiding intrusion into either crop land or the unmanaged riparian forest. For the latter, we identified suitable locations for 10-m wide conservation waterways within agricultural fields that are not recommended for row crop production.

Methods

A GIS was used to define the study area limits as well as the more detailed and intensive identification of biofuel-production zones within the study area. Work was done using Esri's ArcMap 10.3® software, with analytic processes relying heavily on the use of tools provided in the Spatial Analyst module of ArcMap.

The study area corresponds to the limits of several subecoregions within Georgia, USA, pertaining to the Southeastern Plains of the US Environmental Protection Agency's (US-EPA) Level III ecoregion framework [35, 36]. These areas are generally coincident with the Georgia portions of the Southern Coastal Plain major land resource area (MLRA 133A) defined by the USDA-NRCS [37]. The core of the study area includes the following US-EPA Level IV ecoregions: the Dougherty Plain (65 g), the Tifton Upland (65 h), the Coastal Plain Red Uplands (65 k), the Atlantic Southern Loam Plains (65 l), and the Bacon Terraces (75 h). To ensure continuity and eliminate gaps, the selection limits were expanded with a 3.6-km buffer, and all areas outside of the Georgia state lines were excluded, resulting in a single, contiguous area of interest (AOI) of 63,382 km^2 (24,472 mi^2) across the southern half of Georgia (30.6° N to 33.4° N, 81.4° W to 85.1° W; Fig. 1). The region is characterized by gently sloping hills and broad floodplains with an average elevation of 78 m above mean sea level and slopes of less than 3 %. The NRCS soil survey provides a general categorization of land as prime farmland, farmland of statewide importance, not prime farmland, and prime farmland if protected from flooding. Over half of all land in Coastal Plain region is classified as prime farmland or farmland of statewide importance, but for agricultural land uses, four fifths of the land falls into these categories. Soils on higher ground tend to be well drained and highly suitable for crop production. This is reflected in the physical characteristics of crop lands, which are higher and a bit flatter than the AOI as a whole. By contrast, soils in lower areas are poorly drained and subject to flooding. Climate in the region is generally hot and humid with mild winters, with temperature and precipitation increasing across a gradient from north to south. The region falls within USDA Plant Hardiness Zones 8a and 8b. The growing season for the Southern Coastal Plain averages 250 frost-free days per year, and average annual temperatures are 13 to 20 °C (55 to 68 °F). In 2014, one third of the land use in the study area was committed to agricultural production, including row crops and forages, totaling 2.09 M ha^{-1}. Ninety percent of the remaining land cover, or 3.79 M ha, was forested, as unmanaged forests and plantation timber, while the remaining 0.45 M ha^{-1} constituted "developed" land such as residential and commercial urban space [38]. Land-change dynamics in the ecoregion denote the active timber industry, with the predominant transitions occurring between forest and mechanically disturbed land-cover classes [39].

Spatial Analysis

Source data layers were drawn from the most recent published data available from USDA, USGS, the US Census Bureau, and the University of Georgia, and included information about soils, elevation, hydrology, land cover, roads, railways, utility lines, urban areas, and conservation lands (Online Resource 1). The study-area boundaries were used to extract data conforming to the AOI, which were projected to common geographic coordinate system (UTM 17N, NAD1983). Soil data were derived from the 2014 "Gridded Soil Survey Geographic (gSSURGO)" data for Georgia, a raster-data product with a 10-m cell size [40]. Elevation data were extracted from "National Elevation Dataset 10 m 7.5 × 7.5 minute quadrangles" (NED) [41] tiles covering the broader southern half of Georgia, which were combined into one broad data layer, and then clipped to the AOI. The common 10-m cell size provided the basic unit for most of the raster-based processes used throughout the GIS analysis. The soil grid for the AOI served as a reference grid for analyses, and all output raster data from the various analyses were "snapped" to this data layer, ensuring a precise alignment throughout the analyses. Land cover data were derived from the "2014 National Cropland Data Layer" (NCDL) for Georgia [38] and resampled from a 30-m resolution grid to align with the 10-m gridded soils data. Hydrographic data from the National Hydrography Dataset were used to delineate water features in the study area [42]. We combined vector format geodata of Georgia roads and urban areas from 2014 US Census Bureau's "MAF/TIGER" database [43, 44], with utility lines [45], and conservation lands [46], provided by University of Georgia GIS labs, to mask lands that were unsuitable for biofeedstock production.

The GIS analysis proceeded along two lines according to the research questions, identifying (1) biofuel production zones associated with cropland-forest edges near riparian buffers and (2) biofuel production zones associated with potential grassed waterways within agricultural fields. A key difference between these two approaches is the treatment of agricultural fields. The first avoided the elimination of crop land by locating production zones along the edges of fields, while the second removed marginal land from production where a grassed waterway was indicated but absent. The combination of these two processes created the spatial layout for potential biofuel zones throughout the study area.

The process model used to derive biofuel-production zones associated with riparian buffers ("RB process model") can be characterized as constituting three subprocesses with several steps each (Fig. 2). The first subprocess (steps 1.1–1.3) located 20-m buffer zones at the cropland-forest edge (CRP-FOR). The second subprocess (steps 2.1–2.5*)* identified areas near wetland forests associated with hydric soils and riparian zones. Riparian zones were areas within 400 m of a stream or river, while hydric soils were those designated by the NRCS with a hydric rating of C or D [47]. These were combined with land cover to show wetland forests that were in riparian and hydric-soil zones. A Euclidean distance function was applied to these locations and identified cells within 160 m (~0.1 mi), corresponding roughly to the mean distance value (142 m) of all cells in the raster layer. The results of the first two subprocesses were combined in step 2.6, to identify CRP-FOR zones specifically associated with riparian areas. The final subprocess (steps 3.1–3.5) involved a series of selections to eliminate zones that were considered ineligible for biofuel production because of their small extent (2 ha or less) or location. Locational criteria included land in or near transportation/utility corridors and urban areas (ROW buffer), and areas within conservation lands. The end result of this first process model was a spatial dataset of potential biofuel-production zones, or "RB biofuel zones" associated with crop-riparian adjacencies, from which values of total acreage were summarized.

The process model for deriving for biofuel-production zones associated with conservation waterways in crop fields ("CW process model") relied on a digital elevation model, land cover, and an empirical, qualitative approach to setting threshold criteria (Fig. 3). As with the previous model, the CW process model consisted of three subprocesses with several steps each. The first subprocess (steps 1.1–1.2) used the 10-m digital elevation model along with the series of packaged GIS models in the "Hydology Toolkit" of ArcMap's Spatial Analyst module, to create a grid of drainage values, where each pixel was given a cumulative value of the number of cells draining into it. Aerial photography [48] of a USDA

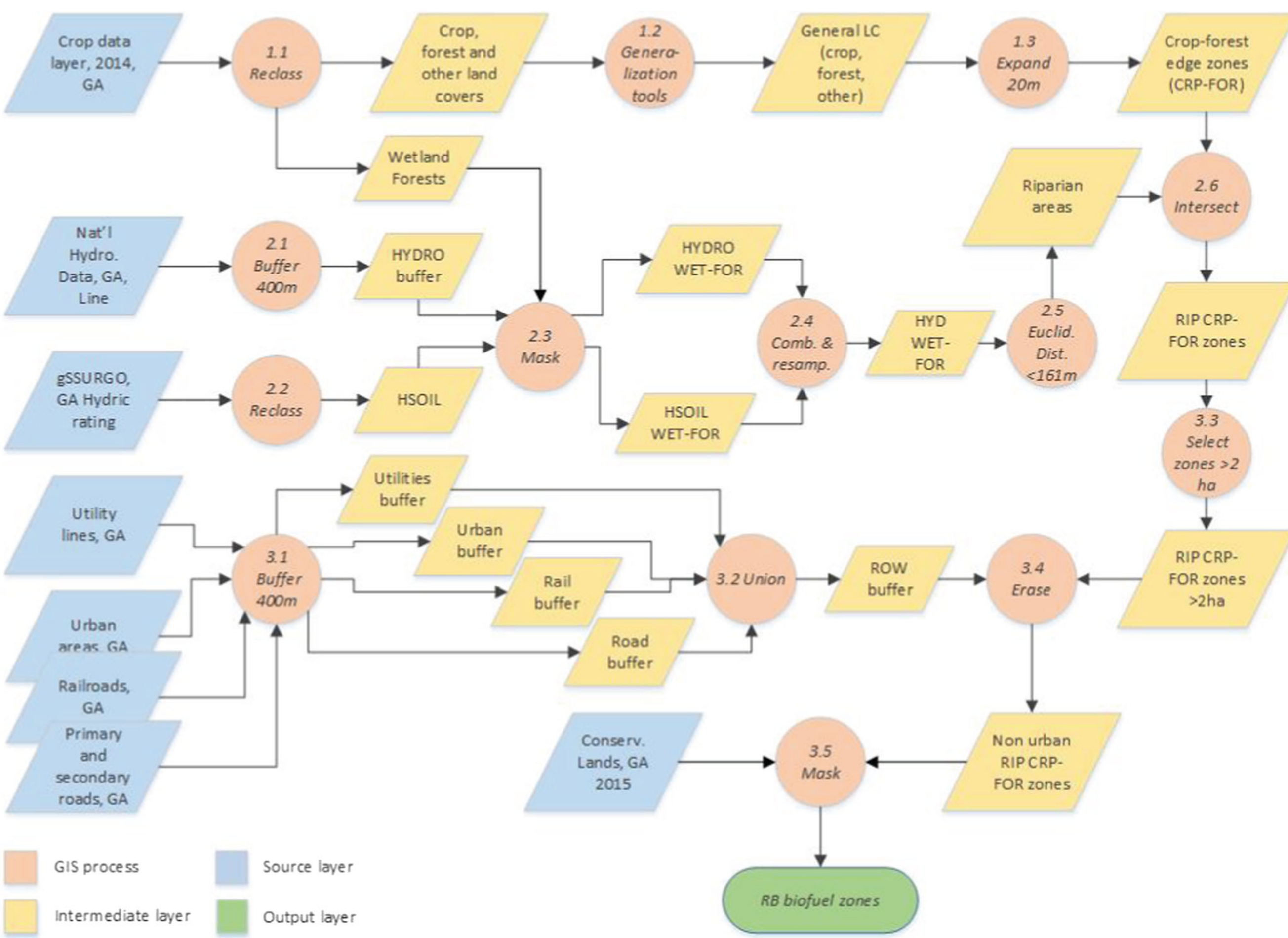

Fig. 2 A GIS process model showing the work flow used to derive *RB biofuel zones*, biofuel production zones at crop-forest edges associated with riparian buffers

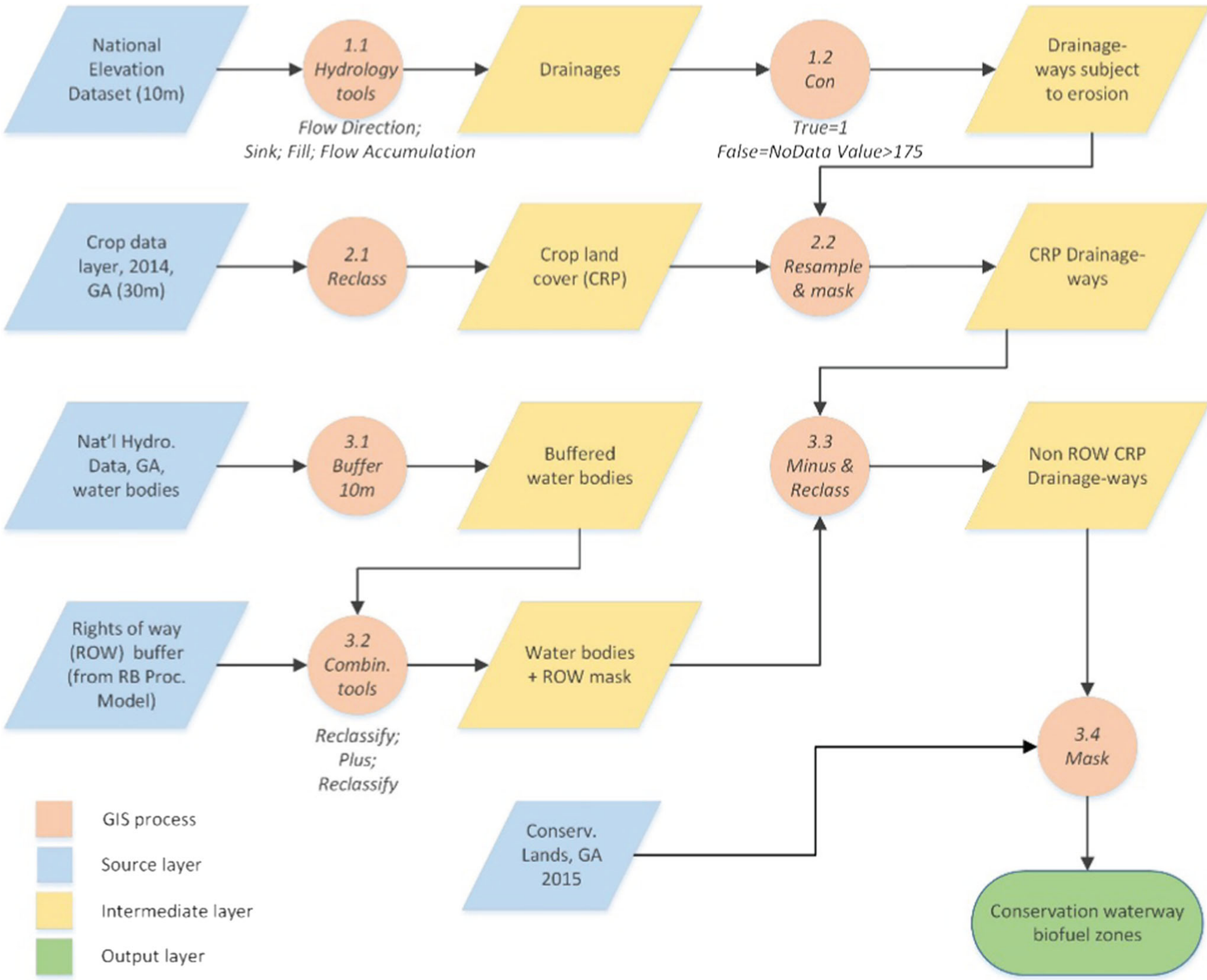

Fig. 3 A GIS process model showing the work flow used to derive *CW biofuel zones*, biofuel production zones located where grassed waterways are potentially located

cooperator farm with exemplary soil-conservation practices was overlain with the drainage values to ascertain the threshold value which best matched the appearance of grassed waterways in the crop fields. A threshold value of 175 was selected, and the grid was reclassified, with a value of 1 assigned to all cells greater than the threshold. The second subprocess (steps 2.1–2.2) used land cover to identify only those drainages that were within crop lands. The final subprocess (steps 3.1–3.3) identified areas near water bodies, such as irrigation ponds, combined with areas within the ROW buffer and conservation lands, and removed these from the total. The end result of this second process model was a spatial dataset of potential biofuel-production zones of conservation waterways within crop fields, the "CW biofuel zones", from which values of total acreage were summarized.

Results from both process models were checked for accuracy by randomly selecting a sample of 310 modeled buffers from each of the biofuel-zone types. Sample zones were visually checked against a background of high-resolution orthoimagery provided by the USDA National Aerial Imagery Program (NAIP 2013) in Google Earth® [48]. If the sample fell along a crop-forest edge, for RB biofuel zones, or within a crop field, for CW biofuel zones, then, it was recorded as valid.

Biofeedstock Production

To estimate potential biofeedstock production, we surveyed published research for yield information on giant miscanthus, switchgrass, and napier grass. We selected results from studies whose conditions roughly corresponded to the field conditions we expect at the edges of crop fields proximal to riparian zones and in potential grassed waterways [17, 18, 49, 50]. As our scenario concept relies on the concentrated nutrients and rainwater runoff from fields as inputs to these marginal lands, we concentrated on yield results from field plots where inputs of fertilizer and irrigation were minimized. For giant miscanthus and switchgrass, we selected yield results from plots grown at similar latitudinal ranges as the Coastal Plain region of Georgia. Although limiting our study to a single ecoregion helped to eliminate extreme variability in environmental conditions, such a large geographic area possesses diverse soil, climatic, and cultural factors. Taking into account the variability of yield responses, we identified plausible values for low, medium, and high yields for each of the perennial grasses (Table 1).

For giant miscanthus and napier grass, we relied on field experiments that are in progress, with full results not yet published, to report some yield values in Table 1. Field data for giant miscanthus were measured in 2014 from 73 sample plots across 7 fields totaling 13.3 ha, located near TyTy, GA, USA (31.44° N, 83.59° W) [T. Strickland, unpublished]. Nutrient inputs to these fields were minimal. No fertilizer was applied, although residue from the previous 2 years was retained, providing a source for organic N in 2014. Average giant miscanthus yields corresponded with results from Florida by Fedenko et al.. Napier grass yields were measured from 2014 experimental plots in Shellman, GA, USA (31.76° N, 84.62° W) [W. Anderson, unpublished]. High napier grass yields in Table 1, published by Knoll et al., were consistent with napier grass yields of 2012 from Shellman experimental plots irrigated with 1.3 cm week^{-1} (0.5″ per week), and fertilized with 168 kg N ha^{-1}.

Nitrogen Removal

To estimate the potential amount of N removed by biofeedstocks in the study, we considered the amount of N incorporated into aboveground biomass by the grasses grown under similar nutrient-input scenarios and assumed that all aboveground biomass would be removed during feedstock harvest. Accordingly, we identified plausible nutrient input levels at field edges and grassed waterway locations, assuming that shallow groundwater and surface-runoff inputs of N would provide a nutrient subsidy to the RB and CW biofuel zones. We used values from the ecoregion published in scientific literature to estimate these subsidies in order to compare the potential nutrient subsidy with the fertilizer input used in trials of bioenergy grasses [51].

Based on measured inputs to a three-zone riparian buffer, Inamdar et al. simulated budgets for total N moving through the riparian buffer using the Riparian Ecosystem Management Model [51] implemented for an experimental buffer in Tifton, GA, USA. Modeled surface and subsurface output from the field area flowing into the grass portion of the buffer were 20.7 kg N ha^{-1} year^{-1}. Near the same location, Bosch et al. reported comparable annual averages of 10.6 and 20.9 kg N ha^{-1} year^{-1} measured for conventional and strip-till fields, respectively, growing cotton and peanuts in rotation

Table 1 Dry matter (DM) yield ranges of giant miscanthus, switchgrass (var. Alamo), and napier grass (var. Merkeron) for the Southeastern USA, Mg DM ha^{-1}

Grass	Low	Medium	High
Giant miscanthus	7.7[a]	9.4[a,b]	11.0[a]
Switchgrass	6.0[c]	15.5[d]	23.5[e]
Napier grass	7.1[f]	19.7[g]	30.1[h]

[a] Second year yield (2014); rainfed; unfertilized; unpublished; low, medium, and high values correspond to first, second, and third quartiles [49]

[b] First year yield (2009); rainfed; mixed unfertilized and fertilized [17]

[c] Fourth year yield average of two experimental cultivars (2009); rainfed; unfertilized [18]

[d] Mean yield of Alamo var. across five sites N30.6° to N33.67°; rainfed; fertilized with 150 kg N ha^{-1} [49]

[e] Twenty-year average yield of Alamo var.; rainfed; fertilized with 84 kg N ha^{-1} year^{-1} [50]

[f] Fourth year yield (2009); rainfed; unfertilized [18]

[g] Fourth year yield (2014); rainfed; fertilized with 168 kg N ha^{-1}; per W. Anderon, unpublished

[h] Second year yield (2007); rainfed; unfertilized [18]

[52]. This reported range fits within our biofeedstock N input range of negligible to 168 kg N ha^{-1} year^{-1} identified in Table 1.

N removal by biofeedstocks, as with yield data, was determined based on a combination of analyses published in the literature and on test results of the 2014 giant miscanthus harvest described previously. For switchgrass and napier grass, we used biomass-N mass fractions (g-N kg^{-1} DM) of 2.7 and 5.7 (respectively), averaged from the first two harvest years published by Knoll et al. [18]. We then combined these values with estimated low, medium and high yields, to estimate the N-removal ranges for those two grasses (Table 2). For giant miscanthus, we summarized statistics for N removal (kg ha^{-1}) at the 73 sample points within a 33-ha farm and reported the first, second, and third quartiles, corresponding with low, medium, and high values [T. Strickland, unpublished]. These N-removal ranges were then used to calculate the potential of N removal by the RB and CW biofuel zones in the study area.

Ethanol Fuel Production

To estimate the potential yield of ethanol produced by biofeedstocks in our study, we referred to ethanol yields published in Dutta et al.. For cellulosic biofeedstocks, approximately 84 gal. US of ethanol are yielded per dry US ton of biomass or 350 l per metric ton [53]. We multiplied this value by our yield estimates to produce a range of total potential ethanol production from the RB and CW biofuel-zone scenarios.

Table 2 Reported N removal ranges of giant miscanthus, switchgrass (var. Alamo), and napier grass (var. Merkeron) for the Southeastern USA, kg ha^{-1}

Grass	Low	Medium	High
Giant miscanthus[a]	22	27	31
Switchgrass[b]	16	41	63
Napier grass[b]	40	100	171

[a] 2014 harvest (TyTy, GA, USA); rainfed; unfertilized; per T. Strickland, unpublished; low, med, high values correspond to first, second, and third quartiles

[b] Biomass N mass fraction (g N kg^{-1} DM) average for 2006–2007 harvests: switchgrass, 2.7; napier grass, 5.7 (see Table 5, Knoll et al., 2012); rainfed; unfertilized [18]

Production Strategies

To estimate the overall impact of biofeedstock production from buffer areas on marginal lands, we envisioned three production strategies that maximized production goals. We recognize that a production strategy would not realistically rest on the sole use of one biofeedstock, for example, napier grass, which we excluded from consideration in the CW biofuel zones. To model production strategies, we focused on production goals, which vary according to policy and economic incentives. The ecosystem services provided by perennial-grass cultivation figured prominently in our selection of goals and led us to a suite of strategies aimed at improving provisioning and regulating services across the landscape [23, 27]. Overarching goals for all models included reducing soil erosion and increasing the options of farmers for sustainable uses of their marginal lands. Further goals driving specific production strategies included increasing agricultural diversity, improving water quality, and enhancing biomass production. For this paper, we selected production strategies focused on maximizing (1) diversity, (2) N removal, and (3) yield. Values were calculated for all three levels of production: low, medium, and high. For "maximizing diversity," the proportion of area designated to each species was maximized within a biofuel zone. So, for example, in RB

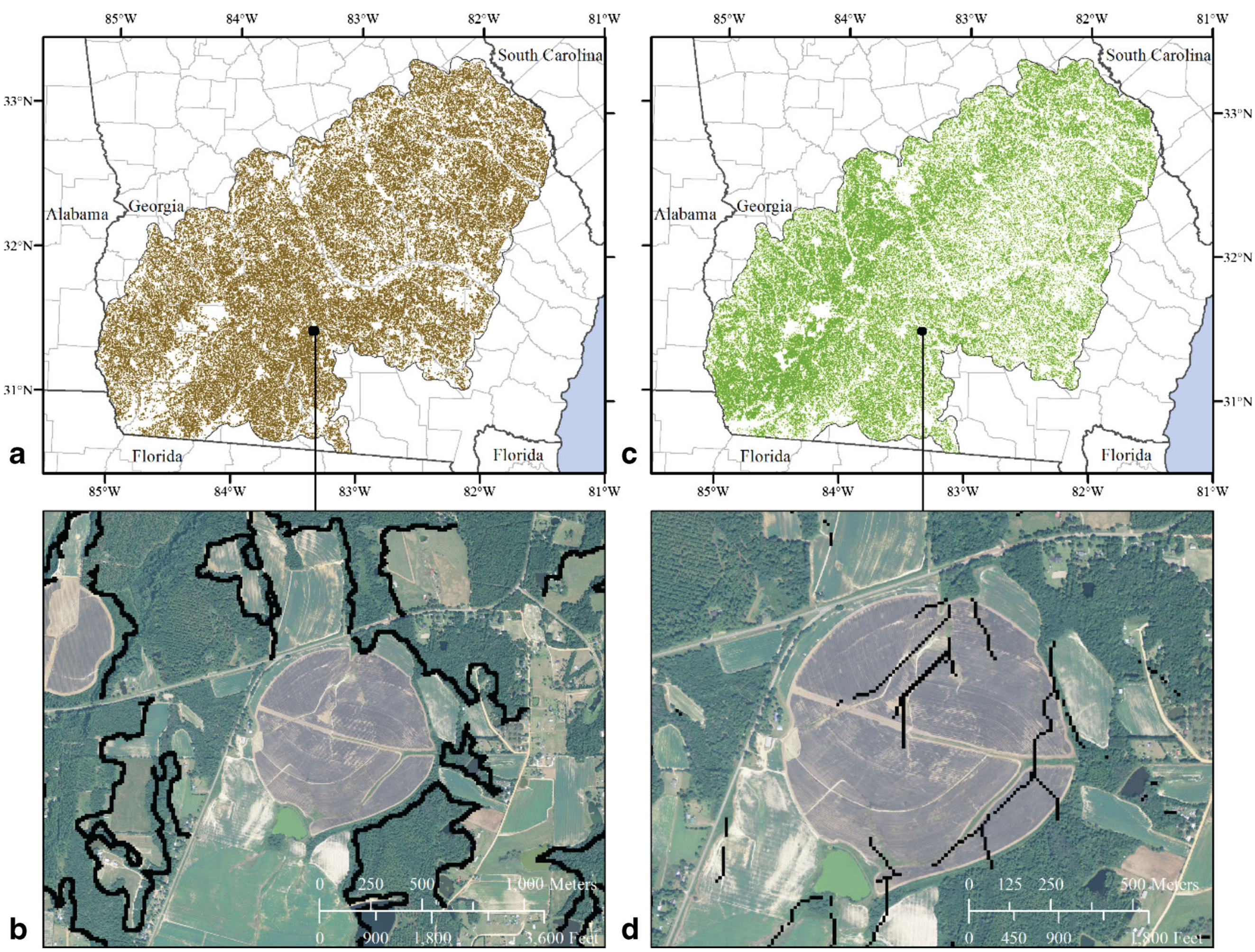

Fig. 4 Map showing examples of modeled biofuel zones: **a** RB biofuel zones associated with riparian buffers and **b** CW biofuel zones associated with grassed waterways (**c** and **d**). Black lines overlain on NAIP 2013 imagery in c and d show RB and CW biofuel zone buffer respectively

Table 3 Proportion of farmland type, mean, and standard deviation of percent slope and mean elevation (mamsl) for the AOI, agricultural lands, and biofuel zones

	Farmland classification (prop)			Slope (percent)		Elevation (mamsl)	
	Prime farmland	Statewide import	Not prime farmland	Mean	Std	Mean	Std
Coastal plain	0.37	0.23	0.41	2.95	3.21	78	29.8
Ag lands in AOI	0.58	0.23	0.19	2.52	2.34	84	29.4
RB biofuel zones	0.37	0.24	0.39	3.46	3.16	81	27.6
CW biofuel zones	0.43	0.23	0.33	1.66	1.85	78	30.4

The fourth category of farmland (prime farmland if protected from flooding) constituted .004 or less of the study area and biofuel-zone scenarios respectively

biofuel zones, where we considered three biofeedstock species, this scenario proposed planting one third of the area with each species. Maximizing diversity values for N removal, yield, and fuel production consisted of the average values of all three grasses for the RB biofuel zones and, for the CW biofuel zones, the average values of giant miscanthus and switchgrass. For “maximizing N removal” and “maximizing yield,” we computed values for grasses having the highest rates of N removal and yield, respectively. Values for all scenarios were calculated at each level of production (low, medium, and high). For each of these strategies, we calculated characteristics of yield, N removal, and fuel production

Results and Discussion

Our analysis identified extent and locations of two biofuel-zone types (Fig. 4) totaling approximately 321 thousand hectares extending throughout the study area. The RB biofuel zones associated with riparian buffers covered 285,140 ha or 89 % of the total. CW biofuel zones associated with grassed waterways constitute the remaining 11 %, 36,520 ha, of the total. General characteristics of slope, elevation and soils of the biofuel zones, crop lands, and the AOI are given in Table 3.

The RB biofuel zones are characterized as 20-m wide strips of perennial sod- or bunch-forming grasses along crop-forest edges that act as buffers bordering large crop fields. Their landscape position is generally downslope from cropped areas, with slightly steeper slopes on average. Perennial grasses in these buffers are well-suited to intercepting surface and subsurface water flow, sequestering excess nutrients, and impeding sediment transport to the riparian forest.

The CW biofuel zones are characterized as 10-m wide strips of perennial sod-forming grasses located in drainage-ways within agricultural fields. Their lower elevations and shallower slopes indicate that these are areas where water would concentrate, and so they are well-positioned to stabilize soils at points in crop fields where gully formation is likely to occur.

Farmland classification for the RB biofuel zones generally followed patterns for the Coastal Plain region. In contrast, CW biofuel zones comprised a higher proportion of prime/non-prime farmland (Fig. 5), although not as high as agricultural lands in the AOI. The biofuel-zone characteristics of lower proportions of prime/non-prime farmlands, lower elevations, and higher slopes in the riparian buffers are indicators of the marginality of these lands.

A random selection of modeled buffers (310 from each type) was validated using NAIP 2013 imagery in Google Earth®. In 78 % of the sample cases, modeled RB biofuel

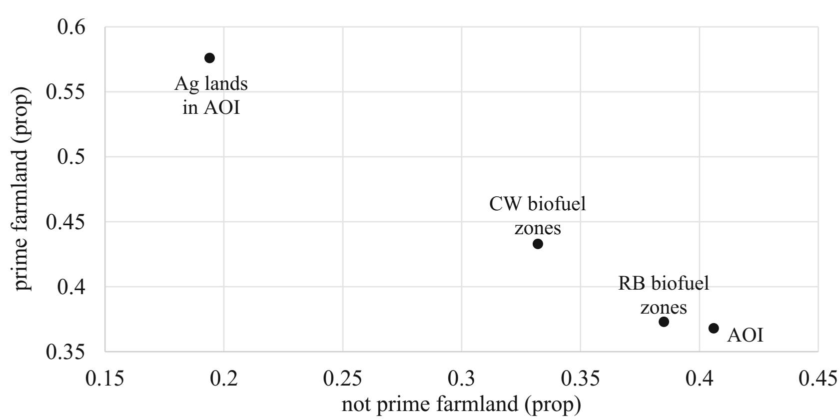

Fig. 5 Proportion of prime vs. not prime farmland in study region and proposed biofuel zones

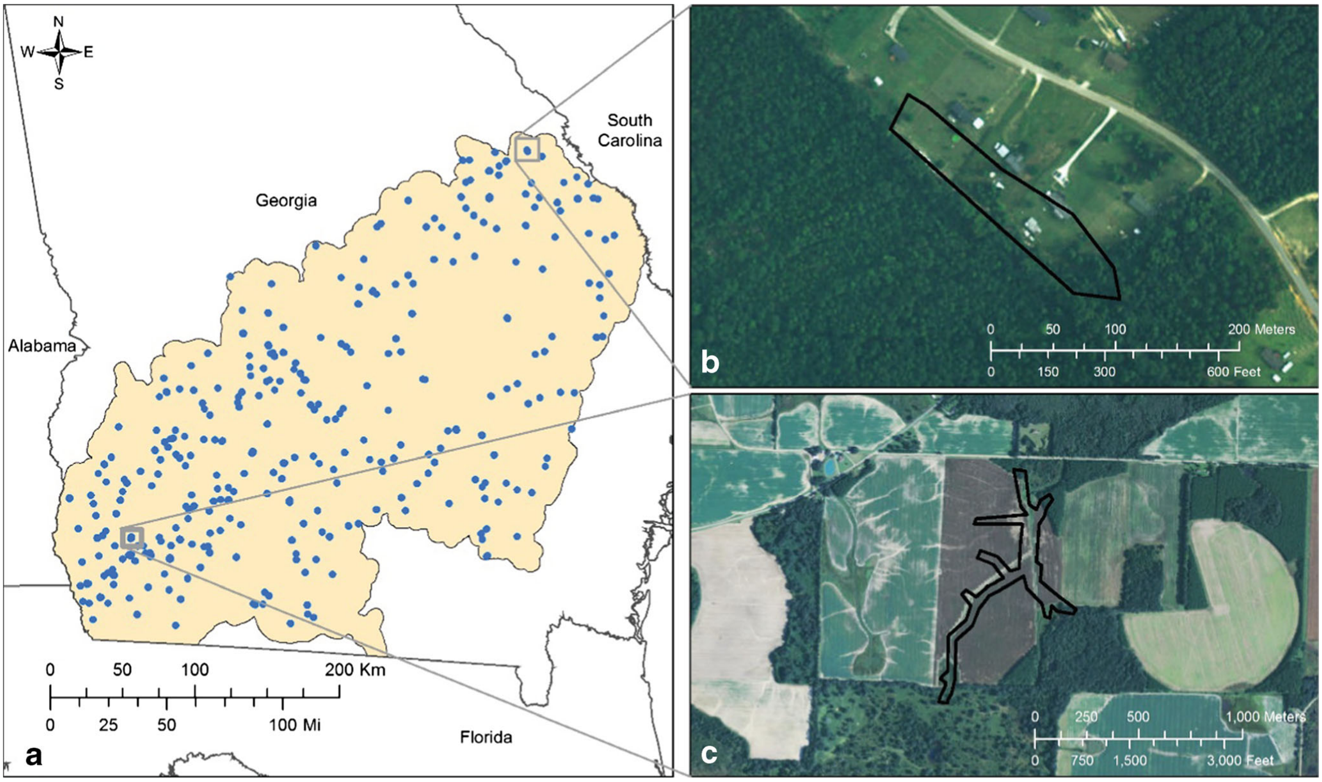

Fig. 6 Map showing randomly selected sample locations of modeled biofuel zones (**a**), with insets showing examples of invalid (**b**) and valid (**c**) sample zones

zones coincided with actual cropland-forest edges and were considered to have accurately identified a potential buffer. For CW biofuel zones, 73 % of the sample cases accurately fell within crop fields and often overlapped with existing grassed waterways. These accuracy checks of both biofuel zone types showed that, in about a quarter of all cases, biofuel zones were indicated by the model where a check of aerial photography showed that the site was not appropriate (Fig. 6). This error

Table 4 Biomass potential for the study area (Tg year^{-1})

	RB biofuel zones (285,140 ha)	CW biofuel zones (36,520 ha)	Total (320,860 ha[a])
Low yield			
Giant miscanthus	2.20	0.28	2.47
Switchgrass	1.71	0.22	1.93
Napier grass	2.02	0[b]	2.02
Medium yield			
Giant miscanthus	2.68	0.34	3.02
Switchgrass	4.42	0.57	4.97
Napier grass	5.02	0[b]	5.02
High yield			
Giant miscanthus	3.14	0.40	3.53
Switchgrass	6.70	0.86	7.54
Napier grass	8.58	0[b]	8.58

[a] Overlap area between zones (~800 ha) is removed from total area

[b] Napier grass is not included in the yield values for CW biofuel zones because we considered it to be unsuitable for planting in these landscape locations

Table 5 N-removal potential for the study area (Mg year^{-1})

	RB biofuel zones (285,140 ha)	CW biofuel zones (36,520 ha)	Total (320.860 ha[a])
Low			
Giant miscanthus	6270	800	7060
Switchgrass	4560	580	5130
Napier grass	11,410	0[b]	11,410
Medium			
Giant miscanthus	7700	990	8660
Switchgrass	11,690	1500	13,160
Napier grass	28,510	0[b]	28,510
High			
Giant miscanthus	8840	1130	9950
Switchgrass	17,960	2300	20,210
Napier grass	48,760	0[b]	48,760

[a] Overlap area between zones (~800 ha) is removed from total area

[b] Napier grass is not included in the yield values for CW biofuel zones because we considered it to be unsuitable for planting in these landscape locations

Table 6 Ethanol fuel production potential for the study area (Ml year^{-1})

	RB biofuel zones (285,140 ha)			CW biofuel zones (36,520 ha)			Total (320,860 ha[a])		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Giant miscanthus	768	938	1098	98	120	141	865	1056	1235
Switchgrass	599	1547	2345	77	198	300	674	1741	2639
Napier grass	709	1756	3004	0	0	0	709	1756	3004

[a] Overlap area between zones (~800 ha) is removed from total area

corresponds to the estimate of overall accuracy of 75.9 % for the row-crop land-cover classes within the NCDL 2014 data layer, which was used as the source for crop land in the models. Additional sources of error likely relate to resampling the coarser resolution land-cover dataset (30 m) to finer resolutions (10 m) and snapping this to the finer grained gSSURGO dataset, confounding classification errors with positional inaccuracies.

Biofeedstock yields for the Coastal Plain were calculated by multiplying estimated yield values of each biofeedstock with the amount of land we identified as suitable land in the RB and CW zones. While, realistically, biomass production from one location to the next would vary according to numerous factors, constraining our study to a single ecoregion delimited by broad isotropic biophysical conditions tempers some of the environmental variability that affects general patterns of plant productivity and yield. Because the modeling processes were independent, a number of pixels classified in the CW biofuel zone overlapped pixels in the RB biofuel zone. This 800-ha area was subtracted from the totals of yield, N removal, and fuel projections for the entire study area. The biomass values of the individual grass species were computed for each biofuel zone (Table 4) giving a range of 1.93–8.58 Tg DM year^{-1} from the selected biofeedstocks. The amount of N removed annually in aboveground biomass would be in the order of ~5100–48,800 Mg N year^{-1} (Table 5) depending on the grass species. Ethanol production, without considering production strategies (Table 6), varies from 674 to 3004 Ml.

The values described in Tables 4, 5, and 6 do not, however, consider potential production based on the goal-oriented strategies. After taking a more reasoned approach, reflecting goals implied in production scenarios, it is not surprising that the ranges for biomass, N removal, and fuel production were generally higher across the board (Table 7). Combining the grass species in a production strategy to maximize yield especially increased biomass levels at high levels of production, topping out at 9.42 Tg year^{-1}. For strategies that maximize yield and maximize N removal, specifying napier grass in the RB zones and switchgrass in the CW zones, medium and high levels of production were essentially the same. However, even at low levels of production, a strategy to maximize diversity in the landscape showed a modest 0.3 Tg year^{-1} increase in minimum levels of biomass production compared to the lowest yielding single species strategy of switchgrass.

To the extent that the perennial grasses take up more N and other nutrients than existing land-cover types, the biofuel zones would provide significant water-quality-filtering benefits to rivers and streams. This concept was clearly illustrated when maximizing N removal was the goal of the production strategy. Here, differences were noted in the potential of these biofuel zones to have an effect, where even at low levels of production, N removal increased by ~1000 Mg year^{-1}. All of this N, along with other constituent elements and compounds of crop field runoff, constitute surplus nutrients that would otherwise be transferred into riparian buffers and waterways.

Table 7 Comparison of alternative production strategies aimed at maximizing diversity, N removal and yield

Production strategy	Characteristic	Low	Medium	High
Maximize diversity: equal amounts of each biofeedstock in each biofuel zone	Biomass (Tg year^{-1})	2.22	4.48	6.75
	N removal (Mg year^{-1})	8090	17,170	26,840
	Ethanol production (Ml year^{-1})	778	1569	2364
Maximize N removal: biofeedstock selected to maximize N removal	Biomass (Tg year^{-1})	2.30	5.57	9.42
	N removal (Mg year^{-1})	12,180	29,940	50,930
	Ethanol production (Ml year^{-1})	805	1950	3296
Maximize yield: biofeedstock types to maximize DM yield	Biomass (Tg year^{-1})	2.47	5.57	9.42
	N removal (Mg year^{-1})	7060	29,940	50,930
	Ethanol production (Ml year^{-1})	865	1950	3296

We estimate that potential biofuel production from marginal lands in the Coastal Plain of Georgia could be substantial. Based on our scenarios of biofeedstock production in buffer areas, coupled with production strategies that maximize diversity, N removal or yield, the Georgia Coastal Plain could produce up to 3296 Ml year^{-1} or a range of 206–871 million gal. US of ethanol from cellulosic biofeedstocks, depending on the level of productivity. This value is somewhat higher than the 56.8 million gallons estimated by Lowrance et al. and translates to a range of 12 to 52 kl km^{-2} (8.4 to 35.6 thousand gal. US mi^{-2}) for the region, inclusive of all land use areas.

Conclusions

Although recent changes to transportation fuels markets have dimmed the research spotlight on biofuels, biofeedstocks continue to offer a valid renewable source of fuel that can profoundly alter future land use if and when viable feedstock, production, and market mechanisms sync to create sustainable systems. Decades of the CRP enactment has translated into a substantial benefits supporting critical ecosystem services of safeguarding water quality, preventing soil erosion, and preserving biodiversity, including key pollinators and pest predators. Such benefits are especially important in matrices of heavily modified agricultural landscapes where protected areas (i.e., wildlife refugia) tend to be small and poorly connected and where diversified agro-ecosystems enhance ecological complexity, improving economic sustainability. One advantage for the production of biofuels in conservation buffers would be to encourage the protection of vulnerable soil and water resources on privately owned land, while providing an economic return for the production of cellulosic feedstocks that do not require regular tillage (e.g., perennial grasses). This study adds to a growing literature of spatial approaches to planning landscape applications of biofuel production incorporating such marginal lands. In this case, we used a GIS-based analysis relying on recent data of elevation, hydrology, land cover, and land use to derive scenarios of potential zones for biofuel production. A number of significant issues remain to be considered, including, for example, the scaling and economic feasibility, or the potential landscape ecological and GHG emissions implications of such biofuel-production scenarios. Nevertheless, our analysis shows that considerable potential exists for biofuel production in the Coastal Plain of Georgia, without disrupting row-crop production or sensitive riparian forests, and while meeting goals for improving water quality and enhancing biodiversity. The use of marginal lands to produce biomass from perennial grasses in and around crop fields in the Coastal Plain of Georgia can potentially meet 1.6 to 6.7 % of the 2015–2022 targeted EISA increase in advanced biofuels from cellulosic biofeedstocks. The actual amount produced will depend on the individual biofeedstock species and clones selected, the level of production, and the production strategy.

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